Spectroscopy and new particles

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Abstract. The properties of three new particles: X(3872), Y(3940) and Z(3931), recently discovered by the Belle collaboration, are briefly reviewed. Negative results of the search for the pentaquark $\Theta(1540)^+$ are also presented.

INTRODUCTION

In the last two years the Belle collaboration has provided evidence for several new hadrons. This paper presents the observation of three new particles: X(3872), Y(3940) and Z(3931). The other new states discovered recently by Belle were also discussed at this conference in separate talks [1, 2]. The paper also presents the results of searches for the pentaquark state $\Theta(1540)^+$. The Belle detector at the KEKB asymmetric e^+e^- collider [3] is a general purpose spectrometer, described in detail in [4].

PROPERTIES OF THE X(3872)

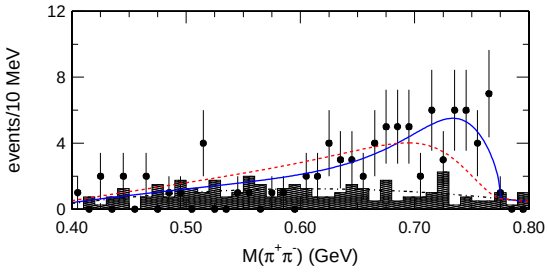

FIGURE 1. The distribution of $\pi^+\pi^-$ invariant mass for events in the $X(3872) \to \pi^+\pi^- J/\psi$ signal region (data points). The shaded histogram corresponds to the background as determined by the X-mass sidebands. The solid (dashed) curve denotes a fit that uses a ρ Breit-Wigner shape with the ρ and J/ψ in a relative $S(P)$-wave. The dash-dotted curve shows a smooth parametrization of the background that is used in the fit.

The state X(3872) was discovered by the Belle collaboration in 2003 [5] by analyzing exclusive decays $B^+ \to \pi^+\pi^- J/\psi K^+$ (charge conjugate modes are included everywhere, unless otherwise specified). The B mesons were reconstructed using two kine-

[1] partially supported by the KBN grant No. 2P03B 01324

matical variables: the energy offset $\Delta E = \sum_i E_i - E_{beam}$ and the beam-constrained mass $M_{bc} = \sqrt{E_{beam}^2 - \sum_i (\vec{p}_i)^2}$, where E_i and $\vec{p}_i$ are the center-of-mass (CMS) energies and momenta of the selected B meson decay products and E_{beam} is the CMS beam energy. A very narrow peak in the invariant mass spectrum of the system $\pi^+\pi^- J/\psi$ was observed with a mass of $3872.0 \pm 0.6 \pm 0.5$ MeV/c^2 and a width below 2.3 MeV (90% C.L.).

The observation of X(3872) was very quickly confirmed by the CDF [6], D0 [7] and BaBar [8] experiments. The observed decay mode $X \to \pi^+\pi^- J/\psi$ seemed to favour the explanation of the X(3872) as an excited charmonium state [9, 10]. However, its properties, in particular the very narrow width, did not allow the identification of the X(3872) with any $c\bar{c}$ state. At the same time the coincidence of the X mass with the $D^0 D^{*0}$ threshold (3871.3 ± 1.0) MeV/c^2) has prompted many theoretical speculations that X(3872) may be a so-called deuson i.e. a loosely bound molecular state of these two mesons [11, 12]. Moreover, the $\pi^+\pi^-$ invariant mass distribution (Fig. 1) was found to peak close to the upper kinematical limit of $M(\pi^+\pi^-)$ as expected for pion-pairs originating from $\rho \to \pi^+\pi^-$ decays.

Recently, the Belle collaboration, using the 253 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance, has provided the first evidence for two new decay modes: $X \to \gamma J/\psi$ and $X \to \pi^+\pi^-\pi^0 J/\psi$ [13]. They were observed in exclusive B meson decays to the final states $\gamma J/\psi K$ and $\pi^+\pi^-\pi^0 J/\psi K$, respectively. The yield of the decay $B \to \gamma J/\psi K$ plotted in bins of the $\gamma J/\psi$ invariant mass (Fig. 2**a)**) exhibits an excess of 13.6 ± 4.4 events (statistical significance of 4σ). The observation of this decay establishes unambiguously that the charge-conjugation parity of the X(3872) is positive. The partial width ratio $\Gamma(X \to \gamma J/\psi)/\Gamma(X \to \pi^+\pi^- J/\psi)$ amounts to 0.14 ± 0.05. This result is in contradiction with the χ'_{c1} (1^{++} charmonium) assignment for X as in this case a value around 40 would be expected. The second decay mode $X \to \pi^+\pi^-\pi^0 J/\psi$ was found to be dominated by the sub-threshold decay $X \to \omega^* J/\psi$. This is motivated by the fact that the yield of B mesons plotted in bins of the $\pi^+\pi^-\pi^0$ invariant mass (Fig 2**b)**) inside of the signal region from the decay $X \to \pi^+\pi^-\pi^0 J/\psi$ is consistent with zero except for the $M(\pi^+\pi^-\pi^0) > 750$ MeV/c^2. There, the excess of 12.4 ± 4.1 events (4.3σ) is observed. The ratio of branching fractions B($X \to \pi^+\pi^-\pi^0 J/\psi$)/B($X \to \pi^+\pi^- J/\psi$). was measured to be $1.0 \pm 0.4 \pm 0.3$, which implies a large violation of isospin symmetry.

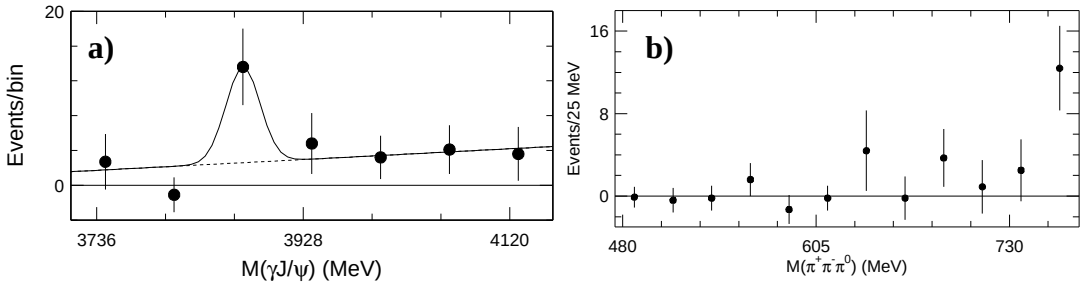

FIGURE 2. The yield of B mesons from the decay **a)** $B^0 \to \gamma J/\psi K$, in bins of the $\gamma J/\psi$ invariant mass and **b)** $B^0 \to \pi^+\pi^-\pi^0 J/\psi K$, in bins of the $\pi^+\pi^-\pi^0$ invariant mass, determined from fits to the ΔE and M_{bc} distributions.

The Belle collaboration also attempted to determine the J^{PC} quantum numbers of the X(3872) [14] by studying the angular distributions of the decay $X \to \pi^+\pi^- J/\psi$, as suggested by Rosner [15]. Among the twelve possible J^{PC} assignments, half (0^{--}, 0^{+-}, 1^{--}, 1^{+-}, 2^{--} and 2^{+-}) may be discarded due to their negative charge conjugation-parity. The value 1^{++} is in agreement with the data while the assignments 0^{-+} and 0^{++} are strongly disfavoured by the analysis of angular distributions [14]. The additional two odd-parity possibilities: 1^{-+} and 2^{-+} are discarded as for them the dipion invariant mass spectrum (Fig. 1) is expected to be much softer to compare with the data. On the other side, the distribution of $M(\pi^+\pi^+)$ is in agreement with the 1^{++} hypothesis. The assignment 2^{++} was strongly disfavoured by the recent, preliminary observation by Belle [16] of the decay $B \to KX,\ X \to D^0\overline{D^0}\pi^0$, where the 11.3 ± 3.6 signal events (5.6σ) concentrate close to the threshold for the final state $D^0\overline{D^0}\pi^0$. In the 2^{++} case, the decay of a spin 2 state to three pseudoscalars ($D^0\overline{D^0}\pi^0$) would require at least one pair of them to be in a relative D wave. In such a configuration the near threshold production would be strongly suppressed by a centrifugal barrier.

All the above observations strongly favour the assignment of $J^{PC} = 1^{++}$ to the X(3872). This matches the expectations of models [11, 12] interpreting the X as a $D^0\overline{D^{*0}}$ bound state. This hypothesis also explains the narrow width of the X(3872) and the shape of $\pi^+\pi^-$ and $\pi^+\pi^-\pi^0$ spectra in its corresponding decays and leads to the prediction of large isospin violation in the X decays. Among alternative interpretations are: a 'conventional' charmonium [9, 10, 17], glueball [18], tetraquark [19] or the so called cusp effect [20].

EVIDENCE FOR THE Y(3940)

In 2004 The Belle collaboration provided evidence for another new state, Y(3940), decaying to $\omega J/\psi$[21]. It was again observed in the B^+ meson exclusive decay to the final state $K^+\pi^+\pi^-\pi^0 J/\psi$. A fit to the $\omega J/\psi$ invariant-mass distribution (Fig.3) yielded a signal of 58 ± 11 events (8.1σ) corresponding to a mass of $3943 \pm 11 \pm 13$ MeV/c^2 and the width $87 \pm 22 \pm 26$ MeV. The Y mass coincides with that of another

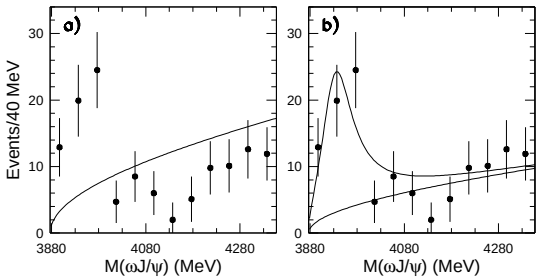

FIGURE 3. $B^+ \to K^+\omega J/\psi$ signal yields vs $M(\omega J/\psi)$. The curve in (a) shows the result of a fit that includes only a phase-space-like threshold function. The curve in (b) corresponds to the result of a fit that includes an *S*-wave Breit Wigner resonance term.

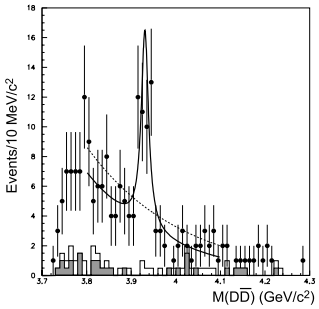

FIGURE 4. Invariant mass distribution of $D\overline{D}$ pairs. The solid (dashed) curve shows the fits with (without) a resonance component. The histograms correspond to the distribution of the events from the D-mass sidebands.

particle, X(3940), also observed by Belle [1, 2]. However, it is unlikely that these two states are the same, since the X(3940) decays to $D\overline{D}^*$ and does not decay to $\omega J/\psi$ and the situation is reversed for the Y(3940), as far as the above-mentioned decays are concerned. The properties of Y(3940) are similar to those expected for the $c\overline{c}-gluon$ hybrid mesons [22].

DISCOVERY OF THE Z(3931)

A recent search by the Belle collaboration for the production of new resonances in the process $\gamma\gamma \to D\overline{D}$ [23] yielded evidence for a new state (Fig. 4) at a mass of $3931 \pm 4 \pm 2$ MeV/c^2 and a width of $20 \pm 8 \pm 3$ MeV. A signal of 41 ± 11 events with a statistical significance of 5.5σ was observed. The properties of this new state match the expectations [24, 10] for the radially excited states χ'_{c0} and χ'_{c2}. A study of angular distributions of the D mesons in the $\gamma\gamma$ rest frame revealed that the data significantly prefer a spin two assignment over spin zero.

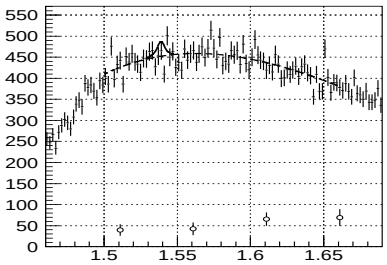

FIGURE 5. Invariant mass spectrum for secondary pK_s^0 pairs and expected yield of the charge exchange reaction per 2 MeV/c^2 (open dots). A fit to a third order polynomial is represented by the dashed curve. The $\Theta(1540)^+$ contribution expected from the DIANA result [26] is presented with the solid line.

SEARCH FOR THE $\Theta(1540)^+$

The Belle collaboration has searched for both inclusive and exclusive production of the $\Theta(1540)^+$ pentaquark using kaon secondary interactions in the material of the detector [25]. An upper limit of 2.5 % (90 % C.L.) was set on the ratio of the $\Theta(1540)^+$ to $\Lambda(1520)$ inclusive production cross section. The search for the exclusive production of the $\Theta(1540)^+$ as an intermediate resonance in the charge exchange reaction $K^+n \to pK_s^0$ yielded an upper limit of $\Gamma_{\Theta^+} < 0.64$ MeV (90 % C.L.) at $m_{\Theta^+} = 1.539$ MeV/c^2. This value is below the current Particle Data Group [27] value of 0.9 ± 0.3.

SUMMARY

The properties of three new particles: X(3872), Y(3940) and Z(3931), recently observed by the Belle collaboration,, were reviewed. For the X(3872) the observation of new decay modes together with angular analysis of the $\pi^+\pi^- J/\psi$ favours the assignment $J^{PC} = 1^{++}$ and is in agreement with the deuson hypothesis. The most plausible interpretations of the Y(3940) and Z(3931) are the $c\bar{c} - gluon$ and χ'_{c2}, respectively. The search for the $\Theta(1540)^+$ yielded a null result giving rise to the limit $\Gamma_{\Theta^+} < 0.64$ MeV (90 % C.L.).

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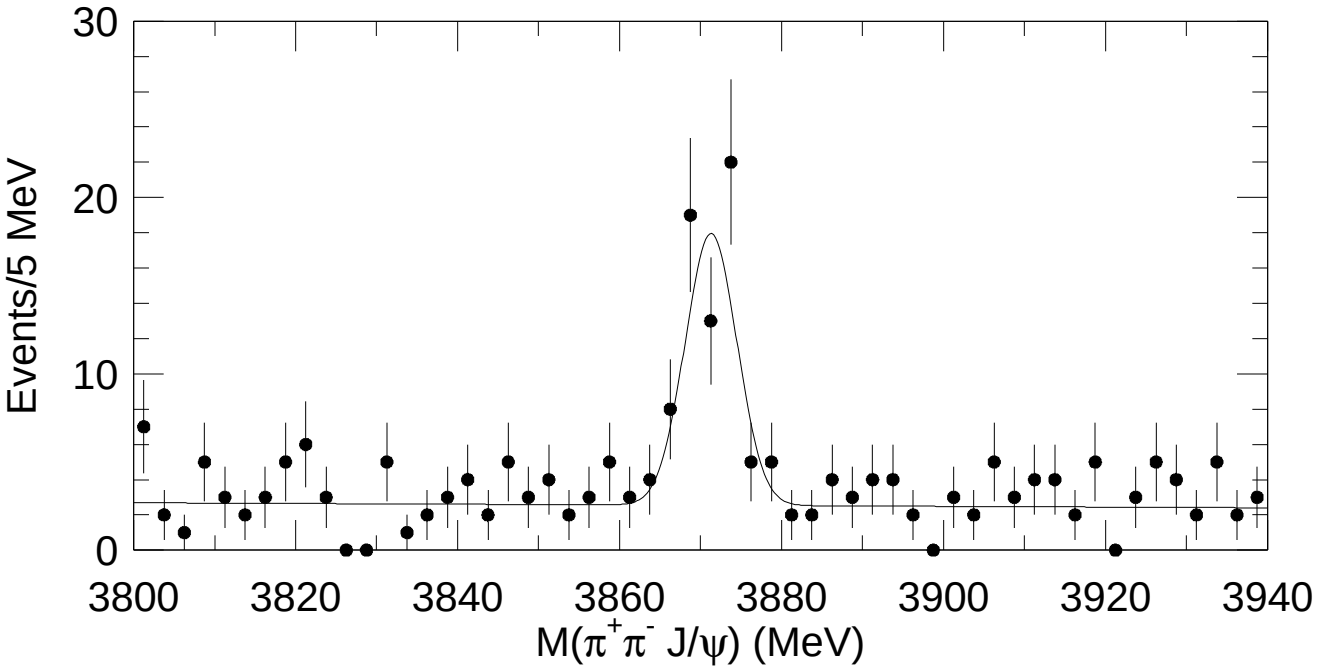
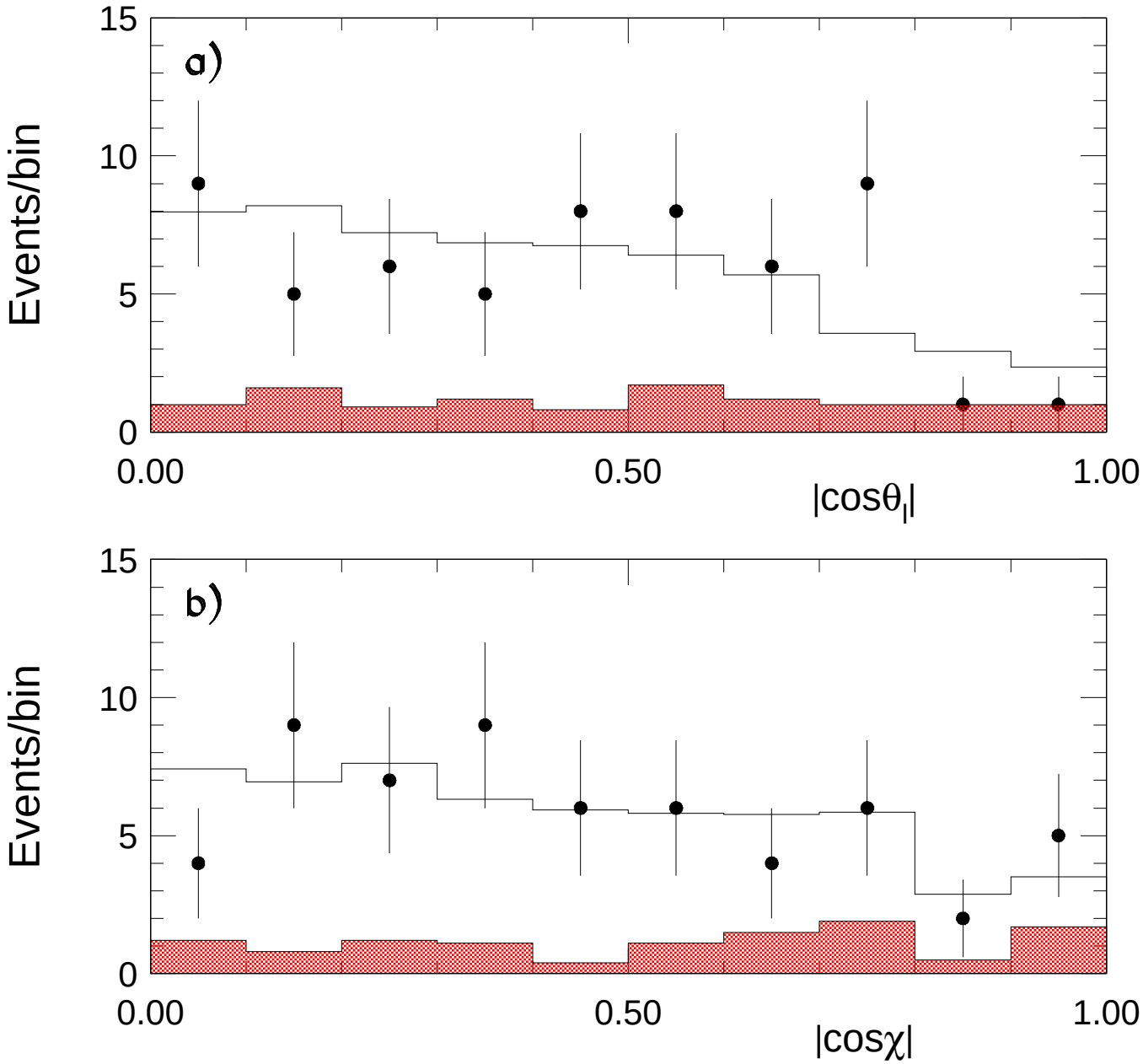

30
20
10
0
Events/5 MeV
3800
3820
3840
3860
3880
3900
3920
3940
M(π+π- J/ψ) (MeV)


a)
Events/bin
15
10
5
0
0.00
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1.00
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b)
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15
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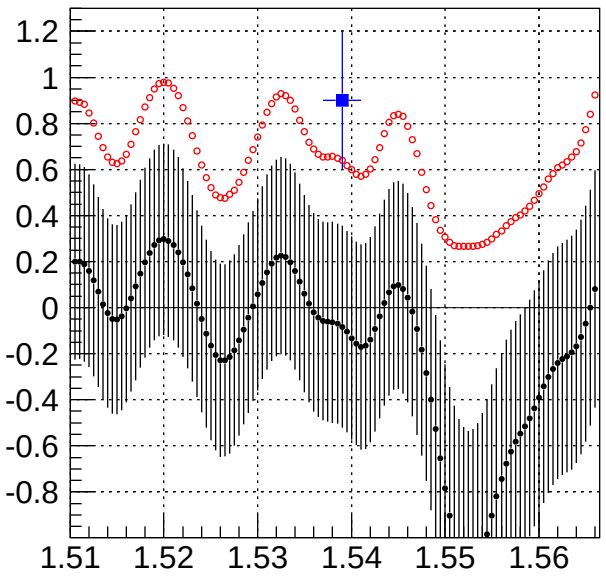
1.2
1
0.8
0.6
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1.53
1.54
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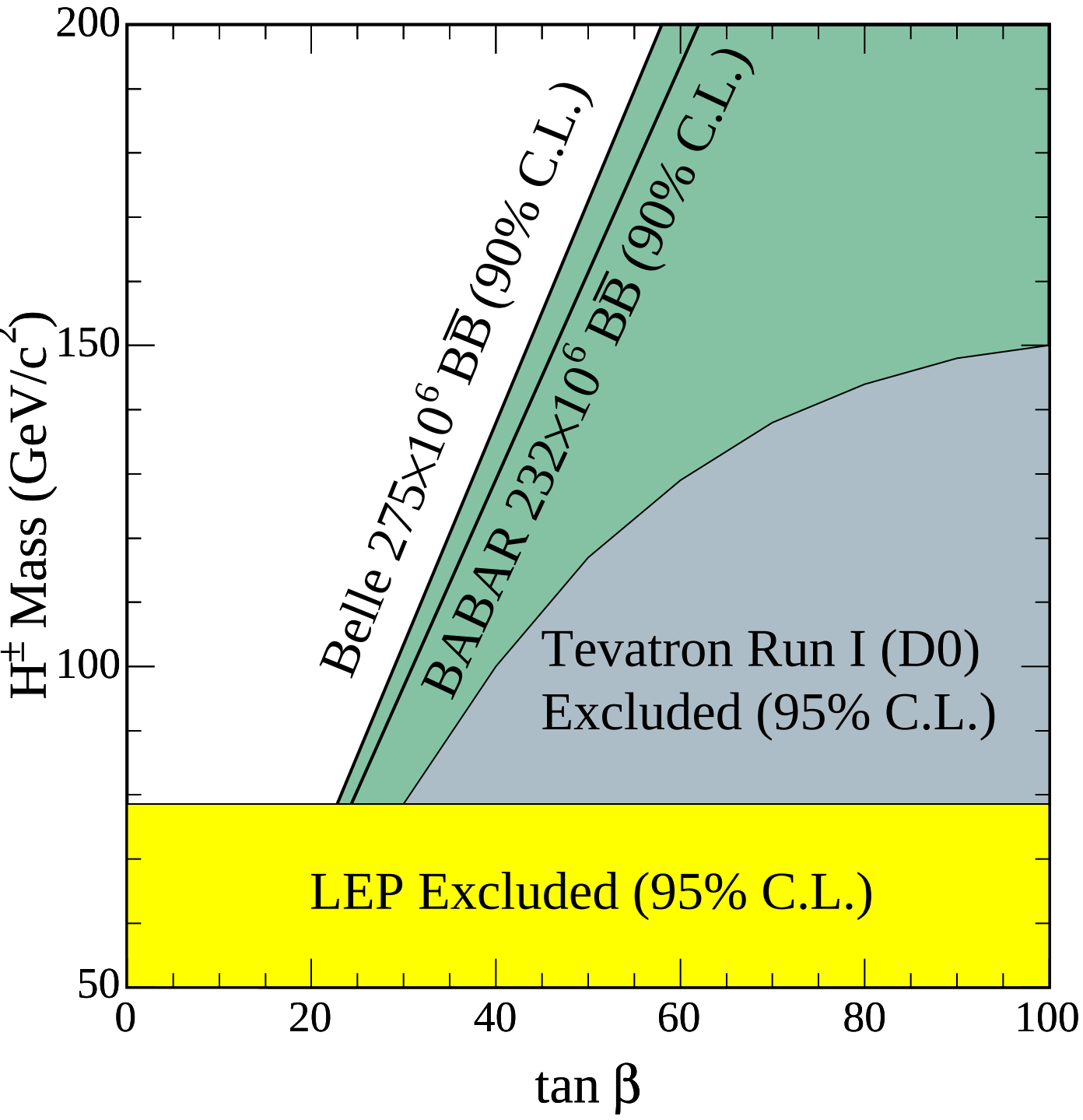
1.56


200
150
100
50
0
20
40
60
80
100
$H^{\pm}$ Mass (GeV/c^2)
tan β
Belle 275×10^6 $B\bar{B}$ (90% C.L.)
BABAR 232×10^6 $B\bar{B}$ (90% C.L.)
Tevatron Run I (D0)
Excluded (95% C.L.)
LEP Excluded (95% C.L.)